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Evaluation of cost functions for FEA based transducer optimization

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Abstract

For a finite element analysis (FEA) based transducer optimization a global cost function is needed to evaluate the simulated model. This global cost function can be composed of several cost functions which describe a certain characteristic of the transducer. By adding weights to these cost functions it is possible to give each characteristic a priority for the optimization.
The goal of this work is to find optimal cost functions for certain transducer characteristics (like bandwidth, sensitivity, sound pressure distribution, angle of beam). For the investigation a simple transducer design consisting of four layers (backing, piezoelectric and two matching layers) is used. Diameter and thickness of each layer are variable.
For the evaluation process a Matlab® script generates different simulation models by modifying the dimensions of transducer layers. For each transducer design four simulation models are generated to determine different criteria: the integrated displacement of the transducer surface, the electrical impedance and the receiver signal assuming two identical transducers by transmission measurement in water. The fourth criterion, the sound field is used for checking purpose only. Each criterion represents a set of cost functions (e.g. for the receiver signal criterion: rise time, maxima, envelope shape…). The significance of the cost functions for different transducer characteristics is evaluated by comparing their results during the different simulations with each other and with the resulting sound field. In this contribution the usability of different cost functions for the abovementioned optimization approach will be presented by means of some examples with different objectives of transducer design.

Keywords: FEA; optimization; transducer; evaluation

1. Introduction

The development of computer technology in the past years and thereby the speedup of computer simulations makes the FEA more attractive for the design of transducers. This technique is used in several optimization approaches like in [1, 2, 3, 4, 5]. Smaller problems were solved using FEA based algorithms several years ago [6]. An important part of the computer aided transducer design is the automatic evaluation of the simulation results by the software. Therefore objective or cost functions are developed which reduce the results to one scalar which should represent the parameters to be optimized. Some works show that one cost function can't represent all parameters, so a sum of different weighted cost functions [7, 8] is used as a global cost function. To be able to compose this global cost function the sensitivity of the different cost functions for the transducer characteristics to

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be optimized have to be known. In this contribution different cost functions are evaluated to describe their sensitivity to characteristics like bandwidth, center frequency, coupling factor and angle of beam. Therefore simple multilayer models of transducers were created and evaluated with each cost function. The results are compared with each other and with the evaluation results made by hand.

2. Simulation environment

The used simulation consists of CAPA (www.wissoft.de) for the FEA-simulation itself and Matlab® for the model generation and post processing. Therefore an own toolbox was build to be able to control CAPA from Matlab®. At the moment it is limited to 2D-models which can solve most optimization tasks. In the preprocessing step the model is generated by the Matlab® toolbox. It is composed of polygons which define the different areas of the model. After defining the areas the mesh of the model is generated. A Delaunay mesher is used to generate a triangle mesh which can represent any shape. Fig.1 shows an example of the used transducer model generated with Matlab®.

After writing the CAPA-simulation file the CAPA simulation is executed. When the simulation is finished the results are imported to Matlab® using the toolbox. The following result types are used in the work:

- Electric potential
- Out of plane displacement
- Velocity potential

Excitations:

- Load impulse
- Sinus burst

It would be much easier to use a commercial tool for the model creation, but building an own toolbox gives much more freedom for modifying the simulation environment and implementing of own optimization functions for further developments.

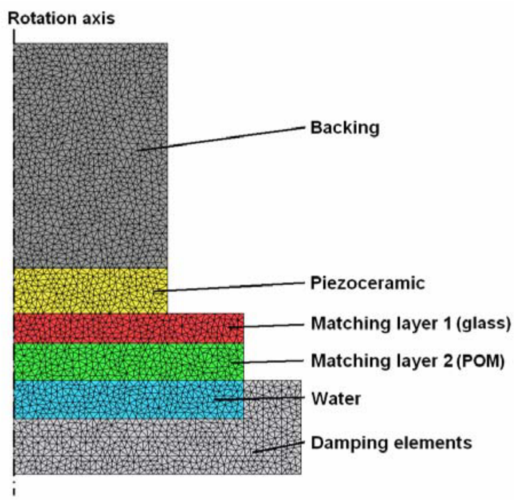

Fig.1 Example of an axis symmetric transducer model generated by the Matlab® toolbox

3. Cost Functions

In this Part the used cost functions are described. They are classified by the result type which is processed. Some of the functions are defined as objective or fitness functions so they have to be maximized for the best result.

3.1. Received electrical signal

A simple cost function is the maximum of the received electrical signal when using two transducers faced to each other in water. This model needs much time for the calculations but it simulates transmitting and receiving and can be used as reference for the other cost functions.

3.2. Electrical impedance

In [2] the admittance of the transducer loaded with air and water is measured. Then an equivalent circuit which consists of a base capacitor and two RLC arms is calculated. The resistance in each arm represents the internal losses and the radiation into the water. With these values the electroacoustic efficiency η can be calculated as

$$\eta = \frac{R_w - R_a}{R_w} \tag{1}$$

where R_a is the resistance measured in air and R_w measured in water. Due to the fact that automatic creation of an equivalent circuit for a transducer having many vibration modes can lead to huge errors a simple function for the evaluation of the impedance is inspected here. It consists of the simulated impedances of the transducer loaded with air Z_a and water Z_w. The difference of the two impedances is calculated at the wanted center frequency ω_t to get a frequency sensitive coupling factor C_ω:

$$C_\omega = \left(|Z_a(\omega)| - |Z_w(\omega)| \right)\Big|_{\omega=\omega_t} \tag{2}$$

3.3. Displacement

The function used to rate the displacement is the integrated out of plane displacement of the transducers surface. Since this is a discrete model the integration is calculated as a sum. In the symmetrical model each point of the surface represents a ring of equal displacements of the round transducer surface. The area of these rings depends on the radius. So the displacements d_i have to be weighted with the depending area A_i during the summation. So the integrated displacement *id* can be written like this:

$$id(t) = \sum_i A_i d_i(t) \tag{3}$$

For the first tests only the maximum of *id* is used.

3.4. Velocity potential

In the simulation the velocity potential of a line in front of the transducer surface is calculated. This is similar to the displacement which is used in function (3), but it represents effects caused by the in plane components of the displacement too. For the further processing the velocity potential is integrated over the area like the displacement. Here the same function (3) as used for the displacement is used, but with the velocity potential vp_i of the point i instead of d_i. Then the maximum over the time of the integrated velocity potential is calculated.

4. Simulation sets

For the evaluation of the cost functions a simple model of a transducer with up to two matching layers and an optional backing is used. The model is axis symmetric and the radius and thickness of every layer are variable. To be sure not to find a local significance of the evaluated cost function a larger domain of the variable parameters is processed. The materials used in these simulations are PIC 255 for the piezoelectric disk, glass for matching layer 1 and polyoxymethylene (POM) for matching layer 2. For the backing an ideal damping material with the same impedance as the piezoelectric disk was implemented. The sinus bursts exciting the transducer have a fixed frequency of 1 MHz.

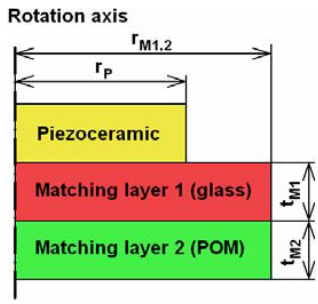

Fig.2 Definition of the variable model parameters

In the different simulations the thicknesses of the matching layers t_{M1} and t_{M2}, the radii of the matching layers r_{M1} and r_{M2} and the radius of the piezoelectric disk r_P as shown in Fig.2 are varied. The thickness of the piezoelectric disk is fixed at 2 mm for all simulations. All models were built in two different versions, one without backing and one with backing. Three mayor sets of simulations are used.

First varies the thicknesses of the two matching layers t_{M1} and t_{M2}. In this set the coupling factor is expected to vary. A change of the angle of beam is neglected.

The second set is nearly the same as the first one except of the radii of the matching layers r_{M1} and r_{M2} which is smaller than in the first set. Compared to the first simulations the angle of beam should be different.

The third varies the radii of the piezoelectric ceramic r_P and the matching layers r_{M1} and r_{M2}. In this model the thickness which gives a good coupling factor is chosen from the first simulations. This set of simulations generally varies the angle of beam.

5. Results

The results of the simulations with the models without backing are shown in Fig.3 and Fig.4. It can be seen that the visualizations for the integrated displacement and the integrated velocity potential are similar. In Fig.3b and Fig.3c both show a periodicity of their relative maxima of about λ/2 which is also known from the analytic calculation of the coupling factor [9]. The results of the simulation of the received electrical signal shown in Fig.3a looks quite similar to the results of the displacement and the velocity potential, but the relative maxima are shifted to smaller values of the first matching layer. This could be caused by the influence of the angel of beam for the used simulation setup which causes bigger amplitude of the received signal even when the coupling factor is not optimal. The influence of the angel of beam can be seen in Fig.4 which shows the results of the simulations for different radii of the piezoelectric disk and the matching layers. For the received electrical signal the results in Fig.4a show a dependency on the radius of these layers. This is expected because the angle of beam depends on the radius of the transducer. The results of the displacement and the velocity potential show only less variation of about 10% as long as the radius of the piezoelectric disk greater than 3.5 mm. If its radius is smaller it is supposed that the piezoelectric disk does not have a dominant vibration mode which could lead to the smaller results in this area.

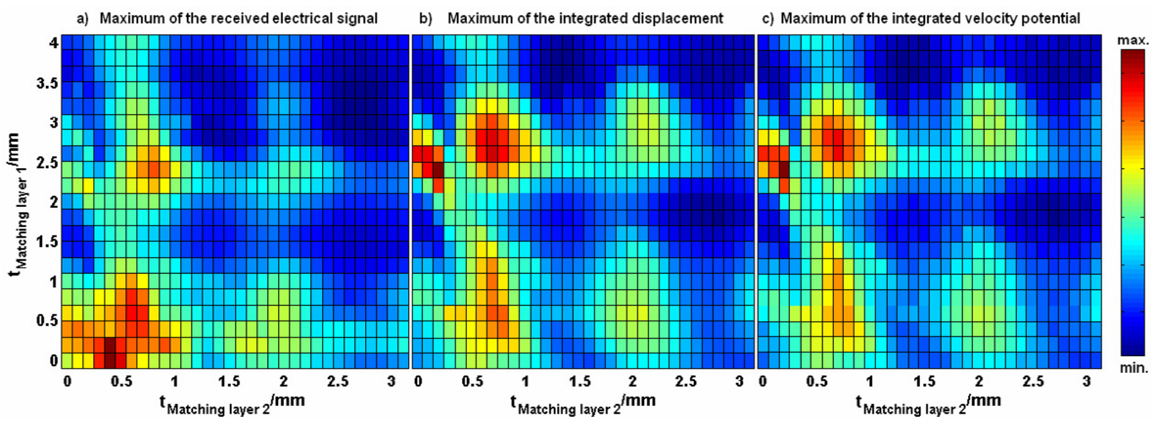

Fig.3 Visualization of different cost functions if the thicknesses of the matching layers are varied. a) Maximum of the received electrical signal, b) Maximum of the integrated out of plane displacement, c) Maximum of the integrated velocity potential

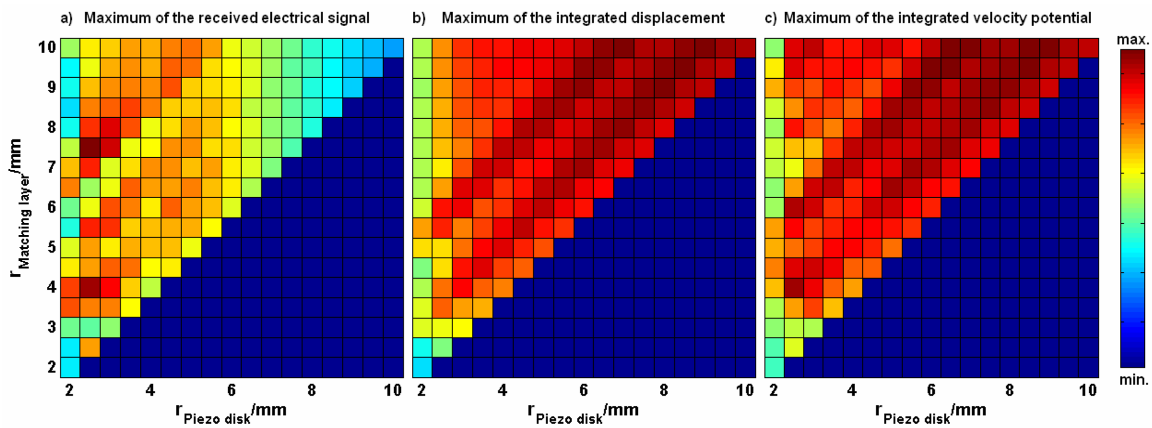

Fig.4 Visualization of different cost functions if the thicknesses of the matching layers are fixed and the radii of the matching layers and the piezoelectric disk are varied. a) Maximum of the received electrical signal, b) Maximum of the integrated out of plane displacement, c) Maximum of the integrated velocity potential

The simulation set with backing leads to similar results. Main differences are a shift of the relative maxima in the cost functions as shown in Fig.5 because of the different resonance condition of the piezoelectric disk and about two times smaller amplitudes of the received signals because of the damping of the backing material.

These results show that the used cost functions based on the displacement and the velocity potential are most sensitive to the coupling factor and less sensitive to the angle of beam. The function used to rate the received electrical signal is sensitive to both, the angel of beam and the coupling factor. It delivers "exact" results if a transducer used for sending and receiving, but due to the large model size the simulation time is very high and it's only useful for verification or for a last optimization step. The displacement and the velocity potential based functions need only small models which lead to less simulation time. This makes these functions useful for a transducer optimization. Due to the fact that the integrated displacement is based only on the out of plane component it is supposed that the integrated velocity potential will deliver better results.

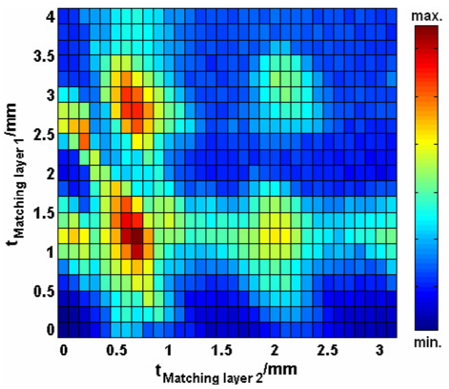

Fig.5 Visualization of the maximum of the integrated displacement if the thicknesses of matching layers are varied, with backing

The results of the cost function using the electrical impedance loaded with water and electrical impedance loaded with air show no significance. If this should be used for an optimization the decomposition of the vibration modes seem to be necessary. However the use of the impedance amount of the water loaded transducer at a fixed frequency shows a period of λ/2 for the relative maxima as expected. So it could be suitable for the characterization of the vibration behavior.

The summary of the results are collected in Tab 1. For each evaluated function the sensitivity and the necessary computation time is rated by symbols from very good ‚++' to very bad ‚--'. The electrical impedance is not listed in the table because the used cost function is not suitable for any optimization.

Table 1. Evaluation of the used cost functions

Cost function	**Simulation time**	**Coupling factor**	**Angle of beam**
Received electrical signal	--	+	+
Out of plane displacement	++	++	--
Velocity potential	++	++	--

6. Conclusion and outlook

In this contribution the usability of some cost functions for a FEA based transducer optimization are evaluated. Therefore a Matlab® toolbox was built to create variable models which are needed to test the cost functions and can be used for transducer optimization as well. It is shown that even simple cost functions which require only small models and less simulation time can lead to similar results as huge models which deliver "exact" results.

For the different test cases about 6700 models were created which can be used for further tests to develop new cost functions for optimization processes.

The test environment and the existing models will be used to analyze more complex functions to find more functions which are sensitive to certain transducer characteristics. Interesting functions are the impulse response of the transducer and the decomposition of the displacement. For the analyzing of the displacement and the velocity potential a point source synthesis as shown in [10] could be use to estimate the sound pressure distribution and the angle of beam.

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